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To cite this article: J C Bellizotti Souza *et al* 2025 *New J. Phys.* **27** 113501

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PAPER

Diode effect for skyrmions interacting with linear protrusion defects

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E-mail: jc.souza@unesp.br**Keywords:** diode effects, skyrmions, annihilationSupplementary material for this article is available [online](#)

RECEIVED

16 August 2025

REVISED

15 October 2025

ACCEPTED FOR PUBLICATION

22 October 2025

PUBLISHED

3 November 2025

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Abstract

We simulate collectively interacting skyrmions in a channel with periodic asymmetry, and find a strong diode effect for the skyrmion flow. There is also an asymmetry in the skyrmion annihilation rate for currents applied along the hard or easy substrate asymmetry direction, with a higher annihilation rate for hard direction currents. We map out the diode efficiency as a function of magnetic field and substrate asymmetry angle. We also show that the Magnus force impacts the diode motion and annihilation rate asymmetry by forcing skyrmions into corners of the protrusion geometry.

1. Introduction

Diode effects are characterized by flow that is easy in one direction and hindered in the other. In electric diodes produced with a p–n junction [1], there is an easy flow of electrons when the junction is positively polarized, and no flow under negative polarization. The use of diodes is essential for modern hardware logic devices. Diode-like behavior has been observed in systems ranging from superconductors [2–5], colloidal particles [6], fluids [7, 8], photonics [9–11], and thermodynamics [12, 13]. For overdamped systems, such as superconducting vortices, diode effects can be produced using a combination of asymmetric potentials, collective particle interactions, and dc driving [3, 4], and the diode effect intensity can be tuned by varying the number of particles that are present.

More recently, skyrmionic diodes were proposed for ferromagnetic skyrmion systems using asymmetric channels [14–17], combining the skyrmion Hall angle with potential edges and barriers [18–20], and by combining spin-waves and transverse fields [21]. Skyrmions are particle-like magnetic textures that form triangular lattices in clean samples [22–24] and can be set into motion by an applied spin current [25, 26]. When skyrmions interact with defects or interfaces, they can experience pinning effects that cause the threshold current for motion to become finite and nonzero [27]. A key feature that distinguishes skyrmion dynamics from the dynamics of most other systems is that skyrmion motion has a strong non-dissipative Magnus force component [24, 27, 28]. The Magnus force causes skyrmions to travel at a finite Hall angle with respect to an external drive and also affects how the skyrmions interact with interfaces, pinning, and other skyrmions [29–31]. The presence of the Magnus force removes the necessity of collective effects usually required for diodes in overdamped systems. The Magnus force also increases the velocity of skyrmions interacting with defects under external driving [14, 32–34], making it possible to achieve rapid skyrmion motion in skyrmionic diode devices.

Recent studies of skyrmion flow made significant progress on understanding how such quasi-particles behave in channels [35, 36], and ratchet effects were observed under different defect arrangements [37–39], potential landscapes [17, 40–42] and magnetic fields [43–46]. Systems in which ratchet effects

appear under ac driving are promising candidates for producing diode effects when collective interactions are introduced. For example, after ratchet effects were identified for individual skyrmions moving over a funnel shaped drive under ac driving [38], it was shown that multiple interacting skyrmions in the same potential could generate diode effects under dc driving. [14]. Ratchet effects of both superconducting vortices [47] and magnetic skyrmions [39] interacting with a linear protrusion defect arrangement have been demonstrated under ac driving. Here, we show that the same type of linear protrusion defect array can give diode motion for multiple interacting skyrmions under dc driving.

We use atomistic based simulations to investigate skyrmion dynamics in the presence of an array of linear protrusion defects under dc driving. Under positive currents, the skyrmions flow in the $+x$ direction with velocities of order 20 m s^{-1} , and the average velocity increases linearly with applied current. For negative currents the skyrmions can move along the $-x$ direction at reduced velocities. This $-x$ motion occurs only for a small current interval, and the flow disappears for most negative current values. The magnetic skyrmion diode effect we observe is characterized by rapid flow along the easy or $+x$ direction and diminished or vanishing flow along the hard or $-x$ direction. The rate at which skyrmions annihilate also depends on the direction of the skyrmion flow, and is less rapid for $+x$ flow and more rapid for $-x$ flow, with complete skyrmion annihilation occurring for large negative currents. The skyrmion trajectories indicate that interactions with the protrusion defects generate a strong Magnus velocity boost for easy direction flow, but that during hard direction flow the moving skyrmions instead interact with pinned skyrmions. The angle of the linear protrusions strongly affects the velocity of the $+x$ flow, since protrusion defects with small angles are more closely aligned with the drag forces on the skyrmions and can more effectively enhance the skyrmion velocity under positive currents. The linear protrusion angle has little to no effect on the velocity of the $-x$ flow. Larger protrusion angles reduce the annihilation probability for both flow directions. Reducing the magnetic field does not modify the $+x$ flow, but the resulting softer skyrmions can deform to a greater extent during $-x$ flow, enhancing the motion. The skyrmion annihilation rate is also reduced when the magnetic field is lowered, indicating that although larger magnetic fields stabilize stiffer skyrmions, these stiff skyrmions are also brittle and are more susceptible to annihilation.

2. Simulation

We use atomistic simulations, which can capture the dynamics of individual atomic magnetic moments [48], to model a ferromagnetic ultrathin film capable of holding Néel skyrmions. Our sample has dimensions of $272 \text{ nm} \times 68 \text{ nm}$ with periodic boundary conditions along the x direction. We apply a magnetic field perpendicular to the sample along the $+z$ direction and work at zero temperature, $T = 0 \text{ K}$.

The Hamiltonian governing the atomistic dynamics is given by [26, 48, 49]:

$$\mathcal{H} = - \sum_{\langle i,j \rangle} J_{ij} \mathbf{m}_i \cdot \mathbf{m}_j - \sum_{\langle i,j \rangle} \mathbf{D}_{ij} \cdot (\mathbf{m}_i \times \mathbf{m}_j) - \sum_i \mu \mathbf{H} \cdot \mathbf{m}_i - \sum_i K_i (\mathbf{m}_i \cdot \hat{\mathbf{z}})^2. \quad (1)$$

The ultrathin film is modeled as a square arrangement of atoms with a lattice constant $a = 0.5 \text{ nm}$. The first term on the right hand side of equation (1) is the exchange interaction with an exchange constant of $J_{ij} = J$ between magnetic moments i and j . The second term is the interfacial Dzyaloshinskii—Moriya interaction, where $\mathbf{D}_{ij} = D \hat{\mathbf{z}} \times \hat{\mathbf{r}}_{ij}$ is the Dzyaloshinskii—Moriya vector between magnetic moments i and j and $\hat{\mathbf{r}}_{ij}$ is the unit distance vector between sites i and j . Here, $\langle i,j \rangle$ indicates that the sum is over only the first neighbors of the i th magnetic moment. The third term is the Zeeman interaction with an applied external magnetic field $\mathbf{H}$. Here $\mu = g\mu_B$ is the magnitude of the magnetic moment, $g = |g_e| = 2.002$ is the electron g -factor, and $\mu_B = 9.27 \times 10^{-24} \text{ J T}^{-1}$ is the Bohr magneton. The last term represents the sample perpendicular magnetic anisotropy (PMA), where we use two PMA constants: $K = 0.02J$ for $i \notin P$, and $K = 5J$ for $i \in P$, with P being the set of defects composing the linear protrusion arrangement shown in figure 1. PMA can be experimentally tuned by thickness modulations [50], irradiating the sample with ions [51, 52], voltage-controlled magnetic anisotropy (VCMA) [53, 54] and lasers [55]. These techniques could be used to create the high PMA arrangement used here. In ultrathin films, long-range dipolar interactions act as a PMA (see Supplemental of Wang *et al* [56]), and therefore merely effectively shift the PMA values. Although reference [56] treats a single skyrmion, the calculations that led to how the dipolar interaction effectively acts did not include any assumptions regarding the presence, or lack, of magnetic textures in the sample; thus the effective interaction obtained in reference [56] is an intrinsic characteristic of thin-films and is valid regardless of the existence of magnetic textures.

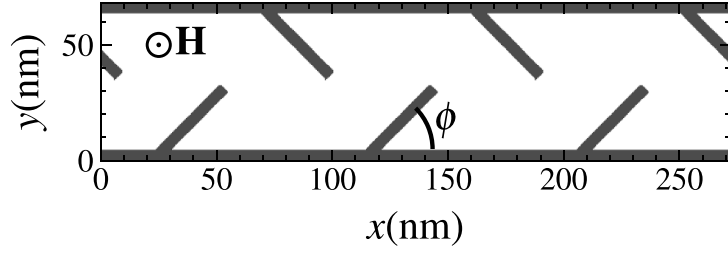


Figure 1. Schematic of the defect arrangement used in this work. Gray regions indicate high anisotropy regions. The angle ϕ is defined as the angle between the x axis and the protrusion. The magnetic field points in the positive z direction, $\mathbf{H} = H\hat{z}$.

The time evolution of atomic magnetic moments is obtained using the Landau–Lifshitz–Gilbert (LLG) equation [57, 58]:

$$\frac{\partial \mathbf{m}_i}{\partial t} = -\gamma \mathbf{m}_i \times \mathbf{H}_i^{\text{eff}} + \alpha \mathbf{m}_i \times \frac{\partial \mathbf{m}_i}{\partial t} + \frac{pa^3}{2e} (\mathbf{j} \cdot \nabla) \mathbf{m}_i. \quad (2)$$

Here $\gamma = 1.76 \times 10^{11} \text{ T}^{-1} \text{ s}^{-1}$ is the electron gyromagnetic ratio, $\mathbf{H}_i^{\text{eff}} = -\frac{1}{\mu} \frac{\partial \mathcal{H}}{\partial \mathbf{m}_i}$ is the effective magnetic field including all interactions from the Hamiltonian, α is the phenomenological damping introduced by Gilbert, and the last term is the adiabatic spin-transfer-torque (STT) caused by application of an in plane spin polarized current, where p is the spin polarization, e the electron charge, and $\mathbf{j} = j\hat{y}$ the applied current density. Use of this STT expression implies that the conduction electron spins are always parallel to the magnetic moments $\mathbf{m}$ [49, 59]. In this work we only consider adiabatic STT contributions, which corresponds to dragging forces perpendicular to $\mathbf{j}$ [26, 60], so dragging forces are along $\hat{x}$ in our system. It is possible to include non-adiabatic STT contributions in equation (2); however, non-adiabatic STT does not appreciably affect the dynamics of nanoscale skyrmions at small driving forces [30], which is the regime we consider. We note that the presence of non-adiabatic STT contributions can affect the skyrmion dynamics and intrinsic Hall angle [49]. Non-adiabatic contributions can usually be neglected when investigating ferromagnets. One special case are Weyl ferromagnets, where the non-adiabatic contribution is large and greatly affects the dynamics of skyrmions [61, 62]. In our case, non-adiabatic contributions can be neglected since they do not affect the skyrmion dynamics significantly under small driving forces [30]. Other types of torques, such as spin orbit torques, can also be investigated, but are not explored in the present work.

The skyrmion velocity is computed using the emergent electromagnetic fields [57, 63]:

$$E_i^{\text{em}} = \frac{\hbar}{e} \mathbf{m} \cdot \left(\frac{\partial \mathbf{m}}{\partial i} \times \frac{\partial \mathbf{m}}{\partial t} \right) \quad (3)$$

$$B_i^{\text{em}} = \frac{\hbar}{2e} \varepsilon_{ijk} \mathbf{m} \cdot \left(\frac{\partial \mathbf{m}}{\partial j} \times \frac{\partial \mathbf{m}}{\partial k} \right), \quad (4)$$

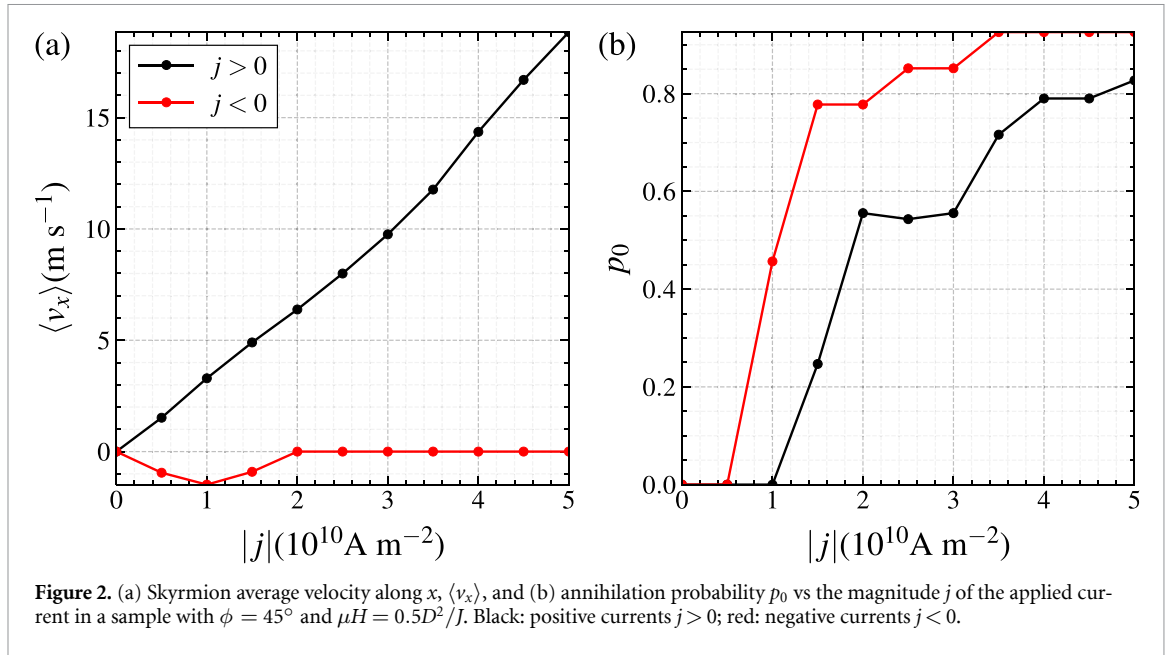
where ε_{ijk} is the totally anti-symmetric tensor. The skyrmion drift velocity, $\mathbf{v}_d$, is then calculated using $\mathbf{E}^{\text{em}} = -\mathbf{v}_d \times \mathbf{B}^{\text{em}}$.

In order to quantify the annihilation present in our simulations, we use the annihilation probability measure, given by

$$p_0 = 1 - \frac{Q_f}{Q_i}, \quad (5)$$

where Q_f is the final number of skyrmions and Q_i is the initial number of skyrmions. Higher p_0 indicates that more skyrmions were annihilated, and lower p_0 indicates that more skyrmions survived.

We fix the following values in our simulations: $\alpha = 0.3$ and $p = -1.0$. The material parameters are $J = 1 \text{ meV}$ and $D = 0.2J$. The numerical integration of equation (2) is performed using a fourth order Runge–Kutta method. For each set of μH and ϕ , the system is initialized with a triangular skyrmion lattice, and then relaxed for 10 ns to allow the skyrmions to adjust to the presence of the linear protrusion defects shown in figure 1. To ensure a steady state for measurement we evolve equation (2) over 200 ns.



3. Diode effect

We first consider a diode effect in a sample with a magnetic field of $\mu H = 0.5D^2/J$ and a protrusion angle of $\phi = 45^\circ$. In figure 2(a) we plot the average skyrmion velocity $\langle v_x \rangle$ versus current amplitude j for positive and negative currents. Under a positive current with $j > 0$, $\langle v_x \rangle$ increases linearly with j , reaching $\langle v_x \rangle \approx 19 \text{ m s}^{-1}$ at $j = 5 \times 10^{10} \text{ A m}^{-2}$. For negative currents with $j < 0$, $\langle v_x \rangle$ slowly increases until $j = -1 \times 10^{10} \text{ A m}^{-2}$, and then it decreases to the value $|\langle v_x \rangle| = 0 \text{ m s}^{-1}$ at and above $|j| = 2 \times 10^{10} \text{ A m}^{-2}$. The significant difference in absolute velocity between positive and negative currents indicates that a diode effect is present, where the flow is easier along the $+x$ direction and harder along the $-x$ direction.

The plot of the annihilation probability p_0 versus current amplitude j in figure 2(b) again indicates that positive and negative currents produce differing behavior. Under a positive current, we find nonzero skyrmion annihilation above $j = 1 \times 10^{10} \text{ A m}^{-2}$, while the onset of annihilation begins at a lower current amplitude of $|j| = 0.5 \times 10^{10} \text{ A m}^{-2}$ for negative currents. In each case, p_0 increases rapidly at lower $|j|$ and then approaches a saturation value of $p_0 = 1$ with increasing $|j|$. For negative currents, the saturation of p_0 is complete at and above $|j_s| = 3.5 \times 10^{10} \text{ A m}^{-2}$, but we do not reach complete saturation of p_0 in the range of positive currents considered here. For all values of $|j|$, the rate of skyrmion annihilation is greater for negative than for positive currents.

To better describe the annihilation process, in figure 3 we plot the skyrmion trajectories at selected values of j . There is no skyrmion annihilation at $j = 1 \times 10^{10} \text{ A m}^{-2}$ in figure 3(a), and the skyrmions interact strongly with the linear protrusion defects while flowing, resulting in a velocity increase via the Magnus velocity boost effect [14, 32–34]. Three well defined flow channels are present, with the first and second closely following the protrusion defect profile, and the third interacting with skyrmions in stagnant areas of the channel. Near the protrusions, we observe compression of the skyrmions similar to those reported by Souza *et al* [65], where a skyrmion size gradient is present. In figure 3(b) at $j = -1 \times 10^{10} \text{ A m}^{-2}$, a portion of the skyrmions are annihilated during the motion. The skyrmions flow primarily in a single channel along the bottom of the sample. A steady state flow is established in which one skyrmion becomes trapped in the acute corner of the bottom linear protrusion defects. This skyrmion undergoes large periodic fluctuations in size as the other skyrmions in the moving channel travel past. At the same time, a trio of skyrmions becomes pinned in each acute corner of the upper linear protrusion defects as a consequence of the chirality exhibited by the skyrmions when interacting with defects [66]. At $j = 2.5 \times 10^{10} \text{ A m}^{-2}$ in figure 3(c), an even greater amount of skyrmion annihilation occurs and the formation of more than one flowing lane becomes impossible. Due to the sign of the current, this lane follows the contour of the upper linear protrusion defects. When the current is reversed to $j = -2.5 \times 10^{10} \text{ A m}^{-2}$, figure 3(d) shows that nearly all of the skyrmions annihilate, and the surviving skyrmions become pinned in the upper and lower acute angles of the linear protrusion defects.

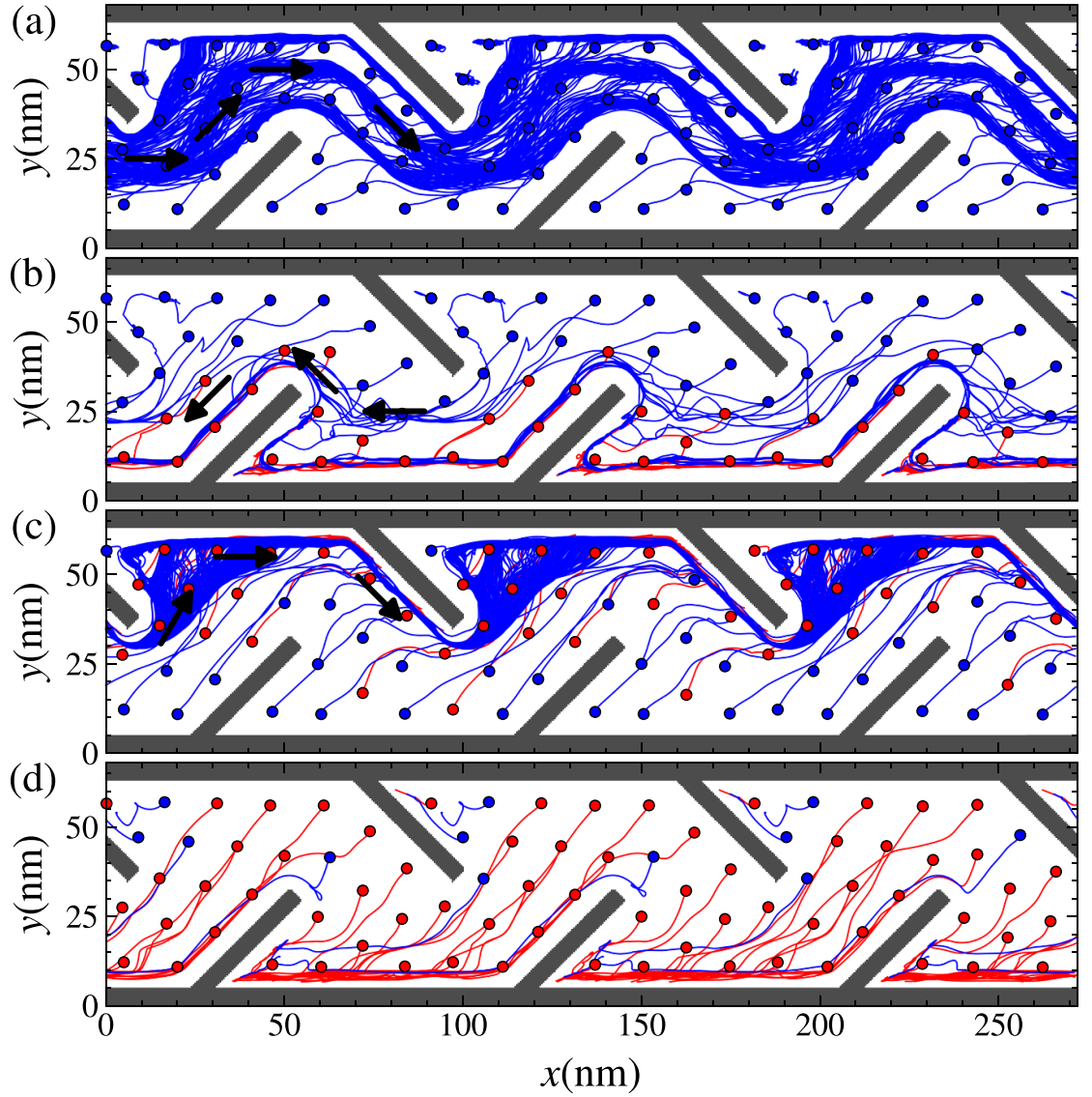
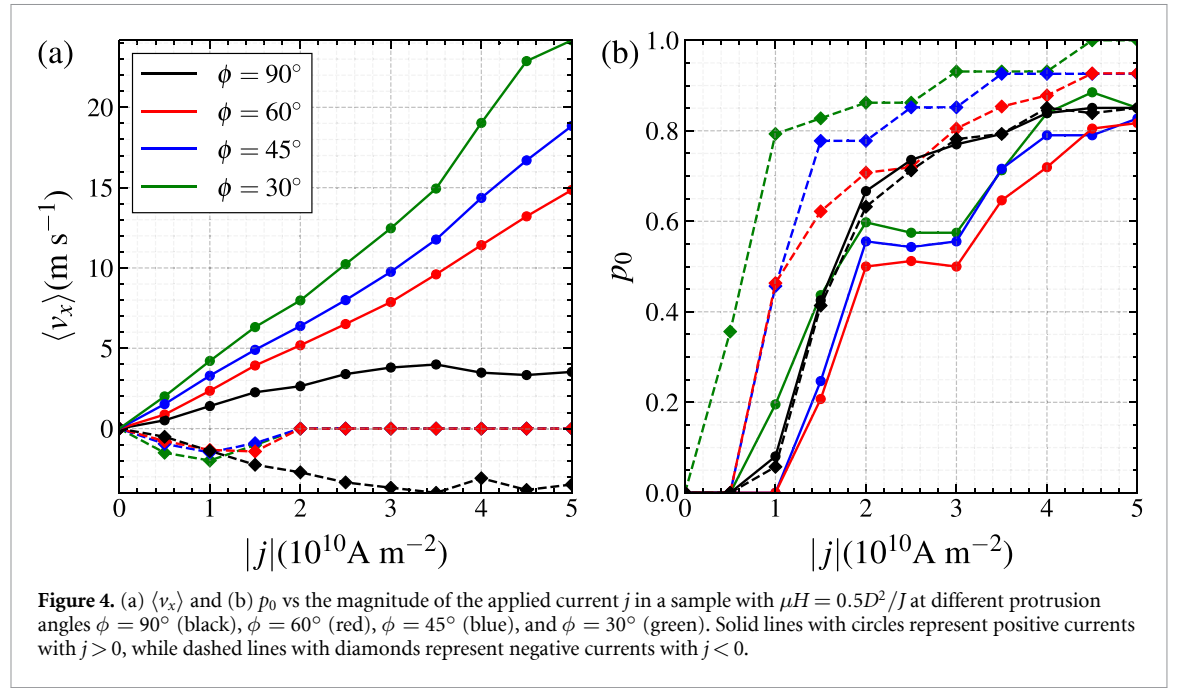


Figure 3. Skyrmion trajectories from the system in figure 2 with $\phi = 45^\circ$ and $\mu H = 0.5D^2/J$ at (a) $j = 1 \times 10^{10} \text{ A m}^{-2}$, (b) $j = -1 \times 10^{10} \text{ A m}^{-2}$, (c) $j = 2.5 \times 10^{10} \text{ A m}^{-2}$, and (d) $j = -2.5 \times 10^{10} \text{ A m}^{-2}$. Blue dots and trajectories: skyrmions that did not annihilate. Red dots and trajectories: skyrmions that annihilated during the flow. Black arrows indicate the skyrmion flow direction. There are no arrows in (d) since most skyrmions annihilate and the system has no skyrmion flow. Animations of the skyrmion dynamics can be found in the supplemental material [64].

4. Varied protrusion angle ϕ

We next study the effect on $\langle v_x \rangle$ and p_0 of modifying the protrusion angle ϕ . Figure 4(a) shows $\langle v_x \rangle$ versus j for different values of ϕ . Under positive currents $j > 0$, the magnitude of the velocity decreases with increasing ϕ . For example, at $j = 5 \times 10^{10} \text{ A m}^{-2}$, we find $\langle v_x \rangle \approx 24 \text{ m s}^{-1}$ when $\phi = 30^\circ$, $\langle v_x \rangle \approx 19 \text{ m s}^{-1}$ when $\phi = 45^\circ$, $\langle v_x \rangle \approx 15 \text{ m s}^{-1}$ when $\phi = 60^\circ$, and $\langle v_x \rangle \approx 3.5 \text{ m s}^{-1}$ when $\phi = 90^\circ$. In contrast, for negative currents $j < 0$, the velocity is only weakly sensitive to the value of ϕ , and in almost all cases $\langle v_x \rangle = 0 \text{ m s}^{-1}$ when $|j| \geq 2 \times 10^{10} \text{ A m}^{-2}$. The exception is that at $\phi = 90^\circ$, the $+j$ and $-j$ behaviors are almost perfectly mirrored across the zero velocity line. The small differences that we find in these two curves are expected to appear as a consequence of the skyrmion chirality when interacting with defects [66].

In figure 4(b) we plot the annihilation probability p_0 versus j for different protrusion angles ϕ . The positive $j > 0$ current behavior for all ϕ values is very similar to the behavior of the $\phi = 45^\circ$ system in figure 2(b), where p_0 increases rapidly with increasing j at low currents before beginning to saturate toward the value $p_0 = 1$ at larger j . For a given value of j , the annihilation probability decreases as



ϕ increases. The onset of skyrmion annihilation falls at $j = 0.5 \times 10^{10} \text{ A m}^{-2}$ for $\phi = 30^\circ$ and 90° , but shifts to higher values of $j = 1 \times 10^{10} \text{ A m}^{-2}$ for $\phi = 45^\circ$ and 60° . Figure 2(b) shows that negative currents with $j < 0$ also give behavior similar to that shown in figure 2(b), with a more rapid increase in p_0 with increasing $|j|$ at low $|j|$ compared to the positive current system, followed by a saturation to $p_0 = 1$ at large $|j|$. We again observe that, for a fixed value of j , increasing ϕ decreases the annihilation probability. Skyrmion annihilation occurs for all negative current values when $\phi = 30^\circ$, while at $\phi = 45^\circ$, 60° , and 90° , the onset of annihilation is at $|j| = 0.5 \times 10^{10} \text{ A m}^{-2}$. For all simulated values of ϕ , the annihilation rate is greater for negative currents than for positive currents, with the exception of $\phi = 90^\circ$, where the annihilation for $j > 0$ and $j < 0$ is approximately the same over the entire range of j considered.

In order to better understand the results of figure 4, in figure 5 we plot representative skyrmion trajectories for different ϕ values at a fixed current magnitude of $|j| = 2.5 \times 10^{10} \text{ A m}^{-2}$. In figure 5(a), at $\phi = 90^\circ$ and a positive $j > 0$ current, the majority of the skyrmions annihilate, while the remaining skyrmions form a single flowing channel following the upper contour of the linear protrusion defects. Some skyrmions remain pinned along the lower region of the sample as a consequence of their interactions with the defects. For a negative $j < 0$ current at $\phi = 90^\circ$, shown in Figure 5(b), a similar behavior occurs with the roles of the top and bottom walls of the sample reversed. For both $\phi = 90^\circ$ systems, when skyrmions interact with the corners at which the linear protrusions meet the confining upper and lower walls, their velocities are increased as a result of a Magnus velocity boost. The boost comes only from the corners and does not occur along the length of the linear protrusions. In figure 5(c), for a positive $j > 0$ current in a system with $\phi = 60^\circ$, approximately half of the skyrmions annihilate. The surviving skyrmions gradually assemble into a single flowing channel following the upper contour of the protrusion defects. Here the Magnus velocity boost becomes very important, since it is produced not only at the corners where the linear protrusions emerge from the boundary walls, but also along the length of the linear protrusion defects. For negative $j < 0$ currents at $\phi = 60^\circ$, Figure 5(d) shows that the majority of the skyrmions annihilate, while the surviving skyrmions become pinned inside the upper contour of the protrusions and cease to move. At $\phi = 30^\circ$ and positive $j > 0$ currents in Figure 5(e), approximately 60% of the skyrmions annihilate. We again find that the surviving skyrmions travel along the upper contour of the protrusion defects, similar to the behavior in figures 3(a), (c) and 5(c). The skyrmion velocity is enhanced by the Magnus velocity boost, but the skyrmions have a higher velocity than in the $\phi = 45^\circ$ and $\phi = 60^\circ$ samples, indicating that the magnitude of the Magnus velocity boost is ϕ dependent. In figure 5(f) at $\phi = 30^\circ$ and negative $j < 0$ current, a majority of the skyrmions annihilate and the remaining skyrmions become pinned by the protrusion defects.

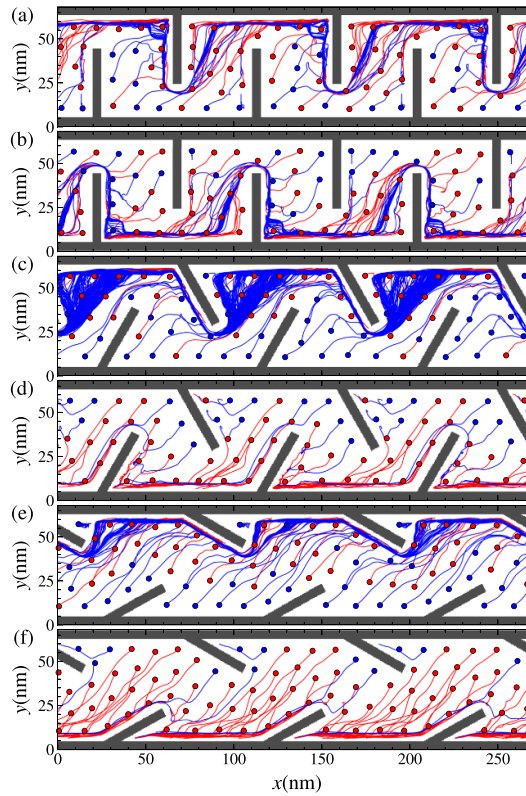


Figure 5. Skyrmion trajectories from the system in figure 4 with $\mu H = 0.5D^2/J$ at (a) $j = 2.5 \times 10^{10} \text{ A m}^{-2}$ and $\phi = 90^\circ$, (b) $j = -2.5 \times 10^{10} \text{ A m}^{-2}$ and $\phi = 90^\circ$, (c) $j = 2.5 \times 10^{10} \text{ A m}^{-2}$ and $\phi = 60^\circ$, (d) $j = -2.5 \times 10^{10} \text{ A m}^{-2}$ and $\phi = 60^\circ$, (e) $j = 2.5 \times 10^{10} \text{ A m}^{-2}$ and $\phi = 30^\circ$, and (f) $j = -2.5 \times 10^{10} \text{ A m}^{-2}$ and $\phi = 30^\circ$. Blue dots and trajectories: skyrmions that did not annihilate. Red dots and trajectories: skyrmions that annihilated during the flow. Due to the skyrmion chirality, the flow along the defect edges is the same as in figure 3 matching the respective sign of the current. Animations of the skyrmion dynamics can be found in the supplemental material [64].

5. Varied magnetic field μH

Next we fix $\phi = 45^\circ$ and vary μH for different values of j . Figure 6(a) shows $\langle v_x \rangle$ versus j at applied fields of $\mu H = 0.3D^2/J$, $0.4D^2/J$, $0.5D^2/J$, and $0.6D^2/J$. Under positive currents $j > 0$, $\langle v_x \rangle$ is affected very little by changes to the magnetic field, unlike the sensitivity of $\langle v_x \rangle$ to the protrusion angle ϕ displayed in figure 4(a). A small amount of variation in $\langle v_x \rangle$ appears only at large values of j , where increasing μH modestly increases the velocity. Much more significant changes in $\langle v_x \rangle$ appear under negative currents $j < 0$, where both the maximum value of $|\langle v_x \rangle|$ and the range of currents over which the velocity is nonzero increase with decreasing magnetic field. There is a small increase in the maximum velocity from $|\langle v_x \rangle| \approx 0.3 \text{ m s}^{-1}$ at $\mu H \geq 0.4D^2/J$ to $|\langle v_x \rangle| \approx 0.4 \text{ m s}^{-1}$ at $\mu H = 0.3D^2/J$. The window of nonzero velocity expands significantly as the magnetic field decreases. For $\mu H = 0.3D^2/J$, $0.4D^2/J$, $0.5D^2/J$, and $0.6D^2/J$, the width Δj of the finite velocity window is, respectively, $\Delta j = 3 \times 10^{10} \text{ A m}^{-2}$, $2.5 \times 10^{10} \text{ A m}^{-2}$, $2 \times 10^{10} \text{ A m}^{-2}$, and $1.5 \times 10^{10} \text{ A m}^{-2}$. When the magnetic field is smaller, or if the anisotropy is decreased, the skyrmions become softer [65, 67], permitting deformations to become important for enabling the flow of skyrmions along the hard or negative x direction. Our results show that it is possible to tune the magnetic field for the purpose of controlling the motion of the skyrmions along the hard direction, so that the skyrmions are mobile under low fields but become pinned under higher fields.

Figure 6(b) shows the annihilation probability p_0 versus the magnitude of the applied current j for different values of μH . Positive currents with $j > 0$ exhibit the same behavior described in figures 2(b) and 4(b), with a rapid increase of p_0 with increasing current for low j , followed by saturation towards $p_0 = 1$ at large j . As the magnetic field increases, the overall magnitude of p_0 increases somewhat, indicating that more annihilation is occurring at larger μH . The onset of skyrmion annihilation is weakly affected by changing the magnetic field, falling at $j = 0.5 \times 10^{10} \text{ A m}^{-2}$ for $\mu H = 0.6D^2/J$ and at $j > 1 \times 10^{10} \text{ A m}^{-2}$ for $\mu H < 0.6D^2/J$. For negative currents with $j < 0$, we observe a rapid increase in p_0 at lower $|j|$, and saturation towards $p_0 = 1$ at larger $|j|$, similar to the behavior in figures 2(b) and 4(b). We find that, for a given current amplitude, the annihilation probability for $j < 0$ is larger than that for $j > 0$.

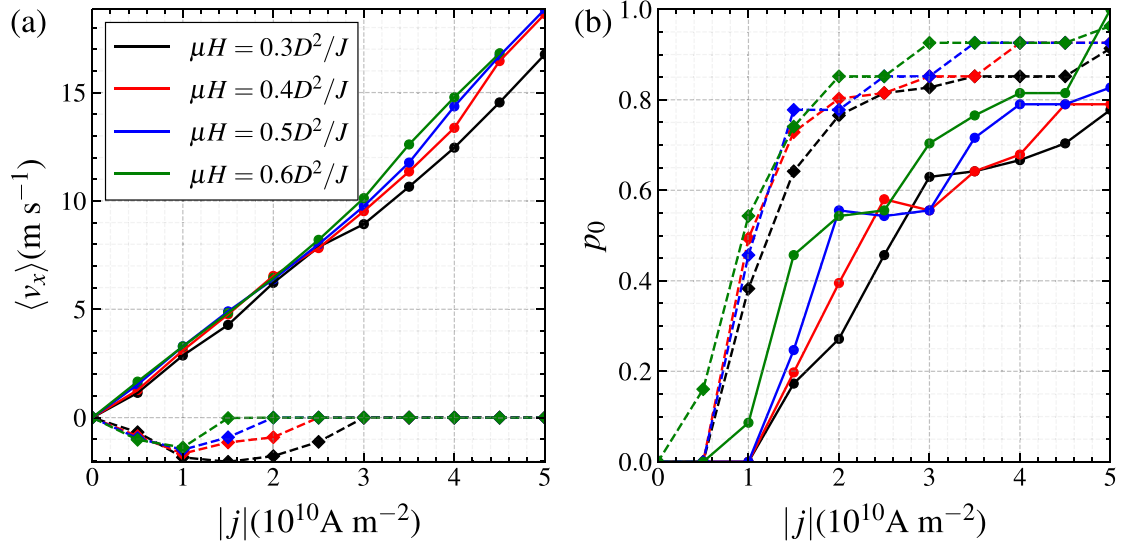


Figure 6. (a) $\langle v_x \rangle$ and (b) p_0 vs the magnitude of the applied current j in a sample with $\phi = 45^\circ$ at different magnetic fields, $\mu H = 0.3D^2/J$ (black), $\mu H = 0.4D^2/J$ (red), $\mu H = 0.5D^2/J$ (blue), and $\mu H = 0.6D^2/J$ (green). Solid lines with circles represent positive currents with $j > 0$, while dashed lines with diamonds represent negative currents with $j < 0$.

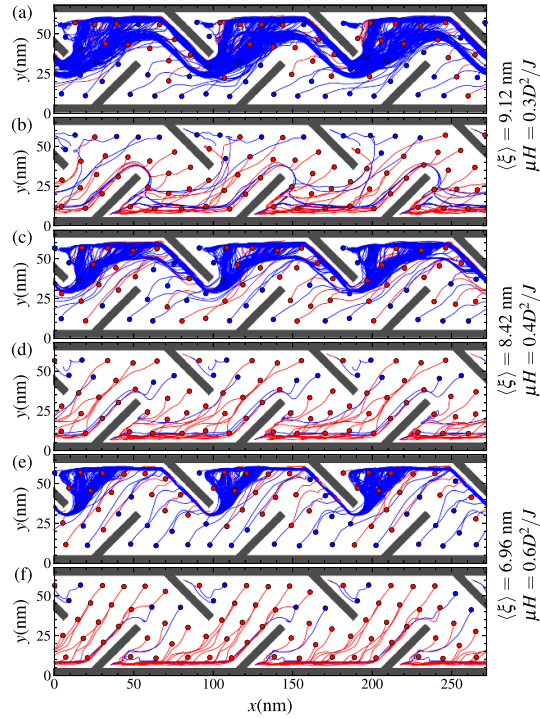


Figure 7. Skyrmion trajectories from the system in figure 6 with $\phi = 45^\circ$ at (a) $j = 2.5 \times 10^{10} \text{ A m}^{-2}$ and $\mu H = 0.3D^2/J$, (b) $j = -2.5 \times 10^{10} \text{ A m}^{-2}$ and $\mu H = 0.3D^2/J$, (c) $j = 2.5 \times 10^{10} \text{ A m}^{-2}$ and $\mu H = 0.4D^2/J$, (d) $j = -2.5 \times 10^{10} \text{ A m}^{-2}$ and $\mu H = 0.4D^2/J$, (e) $j = 2.5 \times 10^{10} \text{ A m}^{-2}$ and $\mu H = 0.6D^2/J$, and (f) $j = -2.5 \times 10^{10} \text{ A m}^{-2}$ and $\mu H = 0.6D^2/J$. Blue dots and trajectories: skyrmions that did not annihilate. Red dots and trajectories: skyrmions that annihilated during the flow. The average skyrmion diameter $\langle \xi \rangle$ at the beginning of the simulation is listed along the side of each pair of plots with the same μH . Due to the skyrmion chirality, the flow along the defect edges is the same as in figure 3 matching the respective sign of the current. Animations of the skyrmion dynamics can be found in the supplemental material [64].

In figure 7 we plot the skyrmion trajectories for $|j| = 2.5 \times 10^{10} \text{ A m}^{-2}$ and $\phi = 45^\circ$ under different magnetic fields μH . At $\mu H = 0.3D^2/J$ and $j > 0$ in figure 7(a), approximately 45% of the skyrmions annihilate. The remaining skyrmions exhibit a Magnus velocity boost and form two channels of flow while interacting with the defects, with the first channel following the upper contour of the protrusion defects, and the second channel following the contour of the first channel. The two channels merge and mix each time the skyrmions reach the upper edge of a protrusion defect, and then reform

when the skyrmions arrive at the next protrusion defect. For a negative $j < 0$ current at $\mu H = 0.3D^2/J$, figure 7(b) shows that approximately 80% of the skyrmions annihilate. One portion of the remaining skyrmions becomes pinned near the corners of the protrusion defects, and facilitates the flow of the rest of the skyrmions along the hard axis by pushing the moving skyrmions over the ends of the lower protrusion defects. Both the pinned and moving skyrmions deform strongly during this motion, and in some cases the moving skyrmions adapt to the shape of the protrusion barrier in the course of jumping over the barrier with assistance from the pinned skyrmions. In figure 7(c), for a positive $j > 0$ current at $\mu H = 0.4D^2/J$, approximately 60% of the skyrmions annihilate. The motion is similar to that found in Figure 7(a), with the skyrmions experiencing a Magnus velocity boost while flowing along the easy axis. There are again two channels of flow, but now the two channels merge before the interaction between the skyrmions and protrusions ceases, indicating that the existence of two (or three, figure 3(a)) channels of flow depends on the rigidity of the skyrmions. Figure 7(d) shows a system with $\mu H = 0.4D^2/J$ for a negative $j < 0$ current, where approximately 80% of the skyrmions annihilate. No persistent motion appears and all of the surviving skyrmions become pinned. The larger value of the magnetic field causes the skyrmions to become more rigid, with reduced deformations, which destroys the hard direction skyrmion flow that was observed at $\mu H = 0.3D^2/J$ in figure 7(b). In figure 7(e) at $\mu H = 0.6D^2/J$ under a positive $j > 0$ current, approximately 55% of the skyrmions annihilate. As in figures 7(a) and (c), the skyrmions flow along the easy direction and experience a Magnus velocity boost. The flow now follows a single channel, with skyrmions moving closer to the upper contour of the protrusion defects and walls. The absence of a second channel of flow enhances the interactions of the skyrmions with the protrusions, resulting in the appearance of a stronger Magnus velocity boost. Under a negative $j < 0$ current at $\mu H = 0.6D^2/J$, figure 7(f) shows that approximately 85% of the skyrmions annihilate. As was the case in figure 7(d), no persistent motion occurs due to the increased rigidity of the skyrmions at the larger magnetic field.

To summarize our findings, in figure 8(a) we plot a heat map of $\langle v_x \rangle$ as a function of ϕ versus j for systems with $\mu H = 0.5D^2/J$. The velocity reaches its greatest magnitude for low values of ϕ , but due to the absence of a hard flow direction for $\phi \leq 10^\circ$, no diode effect is present. A hard flow direction emerges once $\phi > 10^\circ$, and the diode effect becomes visible, as indicated by the appearance of lower velocity magnitudes for negative currents than for positive currents. In the small hatched region with $\phi \leq 30^\circ$ and $j \leq -4 \times 10^{10} \text{ A m}^{-2}$, all of the skyrmions annihilate; very large current amplitudes must be applied to achieve this annihilation. The diode effect occurs across most of the ϕ and $\pm j$ pairs in the phase diagram, but the intensity of the diode motion varies with ϕ . In particular, the diode effect weakens as ϕ approaches $\phi = 90^\circ$, and is lost at $\phi = 90^\circ$ where $\langle v_x \rangle$ becomes symmetric for positive and negative currents. We expect that a mirrored version of the heat map would appear for protrusion defect angles $\phi > 90^\circ$. The corresponding heat map of the annihilation rate p_0 , plotted as a function of ϕ versus j in figure 8(b), shows that there is a higher annihilation rate for negative currents, indicated by the darker areas in the $j < 0$ region.

In figure 8(c) we show a heat map of $\langle v_x \rangle$ as a function of μH versus j at fixed $\phi = 45^\circ$, and the corresponding heat map of p_0 as a function of μH versus j appears in Figure 8(d). The diode effect is present for all values of μH , as indicated by Figure 8(c), but the magnitude of the diode effect increases with increasing μH , as shown by the diminishing magnitude of $\langle v_x \rangle$ with increasing μH in the $j < 0$ region of the plot. This reduction in the magnitude of the velocity with increasing magnetic field is a consequence of the stiffening of the skyrmions and their diminished ability to deform as the magnetic field becomes higher. Figure 8(d) shows that the annihilation rate is greater for negative currents, as indicated by the darker areas in the $j < 0$ portion of the plot. The annihilation rate also increases with increasing magnetic field, and complete annihilation of all skyrmions occurs for large current amplitudes in the high magnetic field regime. This behavior is associated with the brittleness of the skyrmions. At higher magnetic fields, the skyrmions become smaller and more rigid; however, under a sufficiently large dragging force produced by the applied current, they can become brittle and annihilate upon interacting with the protrusion defects.

6. Discussion

Using the results from figure 8, one can tune how strong the diode effect is by changing the magnetic field. Although the diode effect cannot be turned off under arbitrary situations, one can use lower μH and consider only a small j regime to create a system with an almost nonexistent diode effect. In order to turn the diode effect back on, keeping j fixed and applying a stronger μH would create a stronger diode effect.

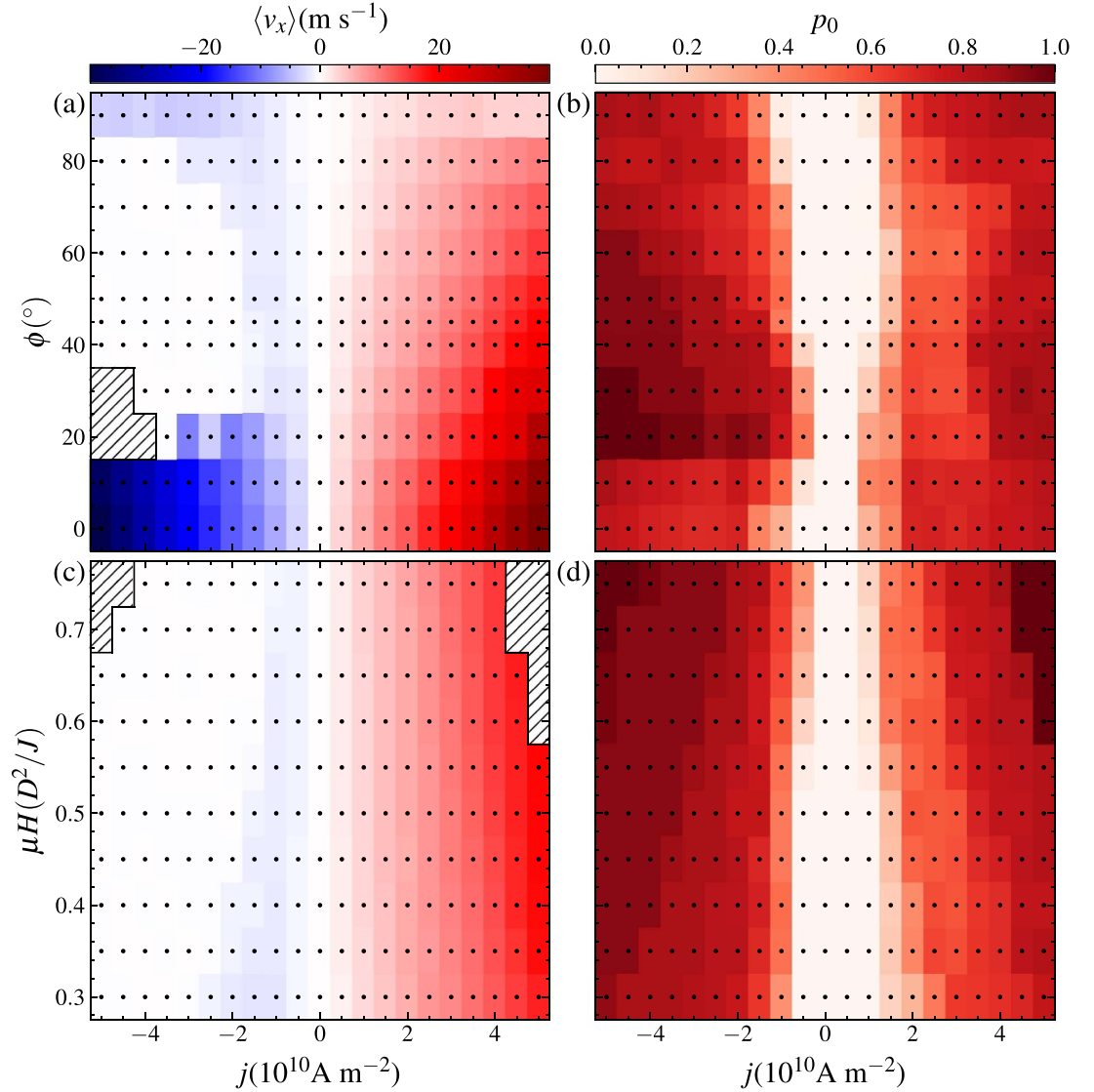


Figure 8. Heat maps of (a), (c) the skyrmion average velocity along x , $\langle v_x \rangle$ and (b), (d) the annihilation probability p_0 plotted as a function of (a), (b) protrusion angle ϕ vs applied current j or (c), (d) magnetic field μH vs applied current j . In (a), (b) we fix $\mu H = 0.5D^2/J$, and in (c), (d) we fix $\phi = 45^\circ$. The velocity color map ranges from dark blue through white to dark red, while the annihilation probability color map ranges from white to dark red. In the hatched regions in (a), (c), there are no surviving skyrmions present.

One of the main mechanisms used throughout this work is the Magnus velocity boost, which enhances the mobility of skyrmions interacting with defects. The Magnus velocity boost arises from the combined interaction of the driving force, the skyrmion Magnus force and the repulsive force from the defects. The driving force pushes the skyrmions towards the defects, which act as a repulsive barrier for skyrmions, but the Magnus term causes the two forces to act not directly in opposition, resulting in a net force on the skyrmion that is larger in magnitude than the original driving force. Due to the velocity rotation caused by the Magnus term, the skyrmion travels along the defect interaction equipotential, as described in [60].

In this work we focus on zero temperature systems; however, temperature effects can play a major role in systems of overdamped particles. Temperature effects are known to introduce creep motion, change the critical drive at which transitions occur [68], and modify the stability of the skyrmions [69]. We expect that the interaction of the skyrmion with the defects should be robust against mild temperature effects. Thermal motion is also affected by the skyrmion chirality [66], and therefore we expect that thermal fluctuations would induce skyrmion interaction with defects in a fashion similar to that of an external drive, but with stochastic behavior.

We use periodic boundary conditions, but real life devices have open boundary conditions. We argue that because of the short timescales considered here, the effects of open boundary conditions can be neglected under relatively simple considerations. For example, a system with $j = 2 \times 10^{10} \text{ A m}^{-2}$ and $\mu H = 0.5D^2/J$, reaches a steady state after approximately 20 ns. Considering a 20 ns steady state time, in the extreme velocity case with $\langle v_x \rangle \approx 20 \text{ m s}^{-1}$, the faster skyrmion would travel on average 400 nm, which is roughly 1.5 times the size of our sample. We expect that for real life applications, where open boundary conditions are present, a device that is 600 nm in dimension, or roughly 2.2 times the size of our sample, would suffice to observe the exact same behavior we report, whereas a sample that is the same size as our system would have a higher annihilation probability and a narrower region where the diode effect is present due to the effects of the finite ends.

7. Summary

Using atomistic simulations, we investigated the dynamics of multiple skyrmions interacting with anisotropy defects forming a linear protrusion arrangement under adiabatic STT currents. We observe a diode effect in which the skyrmion velocity $|\langle v_x \rangle|$ is large for positive $j > 0$ currents applied along the easy or $+x$ direction but reduced for negative $j < 0$ currents applied along the hard or $-x$ direction. The flow direction strongly affects the skyrmion annihilation rate p_0 , with annihilation occurring more rapidly and beginning at lower current magnitudes for negative currents than for positive currents. The annihilation rate increases rapidly with increasing current magnitude for low $|j|$, and saturates toward $p_0 = 1$ as $|j|$ increases. Skyrmions flowing along the easy $+x$ direction experience a Magnus velocity boost during their entire motion, while skyrmions flowing along the hard $-x$ direction do not. The presence of skyrmions pinned in the corners of the protrusion defects is necessary to facilitate the motion of the skyrmions in the hard $-x$ direction, since collective interactions between skyrmions of oscillating size are needed to push the moving skyrmions over the hard direction barrier. If the annihilation rate is too large, no hard direction flow can occur because not enough skyrmions are left in the system, and the remaining skyrmions are all pinned by the defects. The value of the protrusion angle ϕ strongly affects $\langle v_x \rangle$ for easy $+x$ flow since a reduction in ϕ increases the skyrmion velocity due to the Magnus velocity boost. For negative $-x$ flow, $\langle v_x \rangle$ is largely insensitive to the ϕ . Larger ϕ values decrease the skyrmion annihilation rate for both positive and negative currents. The exception is vertical $\phi = 90^\circ$ protrusions, which have the greatest annihilation rate and also show no diode effect due to the lack of asymmetry. When we decrease the magnetic field, for positive currents $\langle v_x \rangle$ is slightly reduced, while for negative currents the window of finite $\langle v_x \rangle$ values is significantly extended. Thus, applying a larger magnetic field enhances the diode effect by reducing the range of j for which motion along the hard axis can occur. Larger magnetic fields stabilize more rigid skyrmions, while smaller magnetic fields produce softer skyrmions that can deform more easily and are better able to travel in the $-x$ direction. The skyrmions also become more brittle when the magnetic field is large, and the annihilation rate p_0 is enhanced. Under extremely large magnetic fields, there is complete annihilation of the skyrmions for large current amplitudes. We expect our results to be useful for designing skyrmion diode devices. The velocity dependence of ϕ together with the ability to control the range of j over which hard direction motion occurs by changing μH can provide a device with fine tuning mechanisms.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

This work was supported by the US Department of Energy through the Los Alamos National Laboratory. Los Alamos National Laboratory is operated by Triad National Security, LLC, for the National Nuclear Security Administration of the U S Department of Energy (Contract No. 892333218NCA000001). J C B S and N P V acknowledge funding from Fundação de Amparo à Pesquisa do Estado de São Paulo—FAPESP (Grants J C B S 2023/17545-1 and 2022/14053-8, N.P.V 2024/13248-5). We would like to thank FAPESP for providing the computational resources used in this work (Grant: 2024/02941-1).

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